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TEMPERATURE AND BLOOD FLOW IN THE HUMAN FOREARM

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The temperature conditions and the rate of blood flow in the human forearm can be affected by alteration of the external temperature, in particular when the forearm is immersed in water at different temperatures (Barcroft & Edholm, 1943). In order to assess changes, it is useful to have some standard for comparison. The standard which has been selected is provided by the conditions existing in the adequately clothed forearm at rest, indoors, at a room temperature of 18–20° C. There have been many previous investigations of both temperature and blood flow in the forearm, but they have dealt mainly with the temperature of the forearm skin (Benedict, 1925; Bazett & McGlone, 1927; Lewis, 1927; Collier & Maddick, 1932), and though blood flow has been measured under various conditions, the limb has always been immersed in water. Bath temperatures of 25° C. (Prinzmetal & Wilson, 1936), 30° C. (Grant & Pearson, 1938), 32° C. (Abramson & Fierst, 1942) and 35° C. (Barcroft & Edholm, 1943) have been used.

The data presented in this paper enable a more rational choice of water-bath temperature to be made by comparing the temperature of the skin, subcutaneous tissue and muscle, and the blood flow of the whole forearm, in the clothed forearm and when the arm is immersed in water at different temperatures.

The opportunity has also been taken to measure the forearm temperature while the uncovered limb was (i) cooling in air and (ii) immersed in water at different temperatures.

METHODS

The subjects were healthy adult males, aged from 20 to 40 years. All experiments were done in a basement room at a mean temperature of 18·5° C., and where the humidity and movement of the air only varied slightly from day to day.

The subject wore his usual clothes in which he felt comfortably warm. The measurement of the temperature of the clothed forearm was made with the subject reclining in an armchair, his clothed forearm resting on the arm of the chair. Before the experiment the position of the veins on the forearm was marked out, since Lewis (1927) has shown that the temperature of the skin in the neighbourhood of a vein may be influenced by the temperature of the venous blood. After

15–20 min. the arm was bared, and the following procedures were carried out as quickly as possible. A hypodermic needle thermojunction 2·5 cm. long was thrust up to the hilt obliquely under the skin covering the brachioradialis muscle, with the tip in the subcutaneous tissue some distance from the nearest vein; a second needle (also 2·5 cm. long) was inserted vertically through the skin into the brachioradialis muscle with the tip near the radius, about 5 cm. distal to the head of the bone. This needle was pushed through the muscle down to the bone and then withdrawn about 1 mm., so that in all subjects temperature readings were taken in the deepest portion of the brachioradialis muscle. Skin temperature was measured thermoelectrically (Lewis, 1927) near the tip of the subcutaneous needle, but avoiding the vicinity of a vein or of an erythematous area apt to appear over the tip of the needle.

In some experiments the temperatures were measured at 5 min. intervals for 2 hr. while the forearm was exposed to the air. In others, subcutaneous and deep-muscle temperatures were taken while the limb was immersed in water. The procedure in these last experiments was the same as described by Barcroft & Edholm (1943).

When the blood flow was measured, cotton-wool was used to simulate clothing. A plethysmograph was fitted to the left forearm (Barcroft & Edholm, 1943). After the diaphragms had been cemented to the skin, the portion of the forearm between them was covered with cotton-wool, as was any exposed part of the arm above the upper diaphragm. The forearm, including the part in the plethysmograph, was in effect clothed. The routine arrangements for recording the blood flow were then completed except that the plethysmograph was not filled with water, and the limb was not immersed in the water-bath. The plethysmograph was carefully protected from draughts.

To ascertain whether the cotton-wool protected the limb from heat loss, a sleeve of it was fitted to the opposite arm, after a thermojunction needle had been inserted into the brachioradialis muscle. A small area of skin could be exposed for the measurement of skin temperature.

In some experiments a larger, 15 cm. diameter, plethysmograph was used. This enabled blood flow and temperature measurements to be made simultaneously on the same forearm. The lead for the thermojunction was taken through the upper rubber diaphragm and the needle was inserted into the limb inside the plethysmograph. The forearm was then covered with cotton-wool as above and the arrangements for recording completed. The thermojunction for the measurement of skin temperature could be manipulated from the outside of the plethysmograph on to a small bare area of skin within.

Blood flow and temperature were recorded every 5 min. for 2 hr.

RESULTS

Temperature measurements

Temperatures in the forearm immediately after baring. Readings of all three of the arm temperatures were obtained within 15–60 sec. of baring the arm, skin temperature being measured first (Table 1).

TABLE 1

	Average temp. ° C.	No. of subjects
Skin	33·0 ±0·62	15
Subcutaneous tissue	33·6 ±0·91	26
Deep muscle	36·2 ±0·56	30
Mouth	36·86±0·11	30

In the fifteen subjects in whom all the three arm temperatures were measured, the averages for the subcutaneous and deep muscle temperature were identical with the larger series shown in Table 1.

The forearm exposed to air. Five subjects were investigated. The results are shown in Fig. 1. The rate of cooling of the deep-muscle layers varied considerably; in the 2 hr. of the experiment in one subject, the temperature here fell 7·4° C., in another, under identical conditions, the temperature only fell 3·7° C. On the other hand, subcutaneous and skin temperatures fell at similar rates in all subjects, the final values being 28·5 ± 0·60 and 27·9 ± 0·46° C.

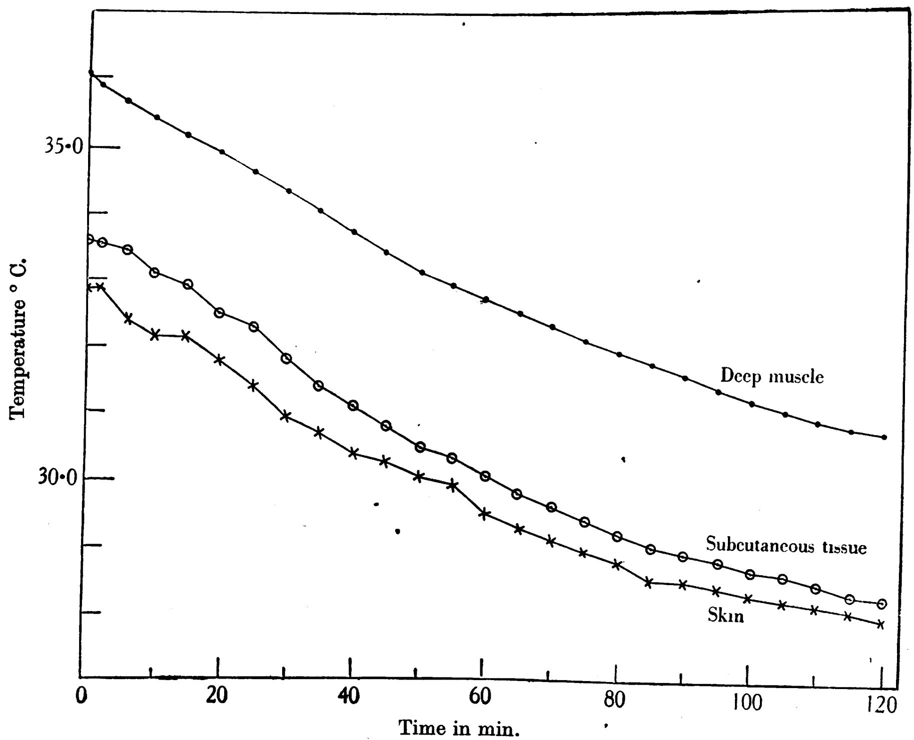

Fig. 1. The skin, subcutaneous and deep-muscle temperatures in the forearm exposed to room air at time 0.

The forearm immersed in water. The number of subjects investigated at each temperature is indicated in Fig. 2 together with the results. With the lower bath temperature there was little difference at the end of the 2 hr. period between the temperature of the bath and that of the subcutaneous tissue. With bath temperatures above body temperature, there was sometimes considerable difference between the subcutaneous temperature and that of the bath.

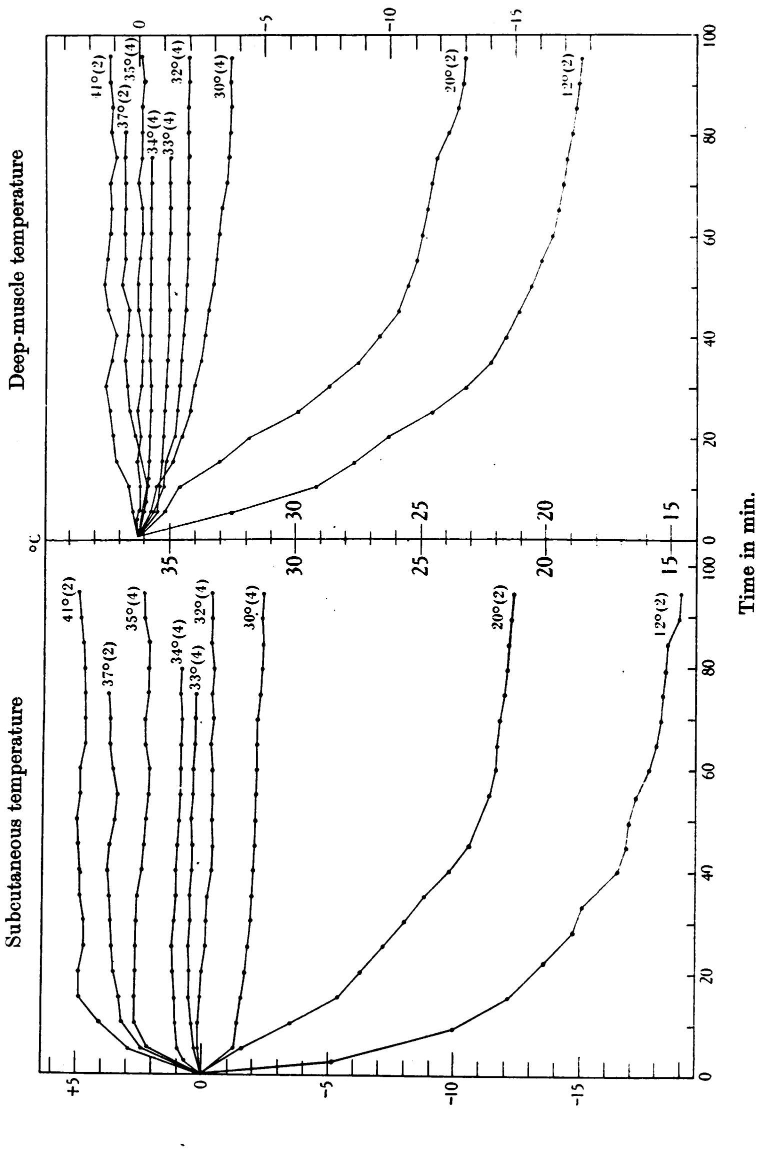

Fig. 2. The subcutaneous and deep-muscle temperatures in the forearm placed in the water-bath at time 0. The water-bath temperature is given above the right-hand end of each curve. In the centre of the figure the ordinates show the subcutaneous and deep-muscle temperature in ° C. On the right and left of the figure the ordinates are given as deviations, in ° C., from the average temperature in the clothed arm; on the left side 0 = 33·6° C., the average subcutaneous temperature in the clothed forearm; on the right 0 = 36·2° C., the average deep-muscle temperature.

Blood-flow measurements

Blood flow in the covered forearm. Seven subjects were investigated. The actual recording of the blood flow with the air-filled plethysmograph presented no difficulties. Fig. 3 shows a typical tracing. The results have been averaged

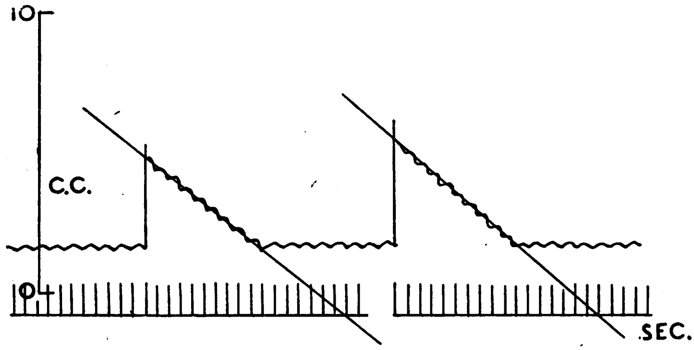

Fig. 3. Tracings of the blood flow in the clothed forearm recorded with the plethysmograph filled with air instead of water.

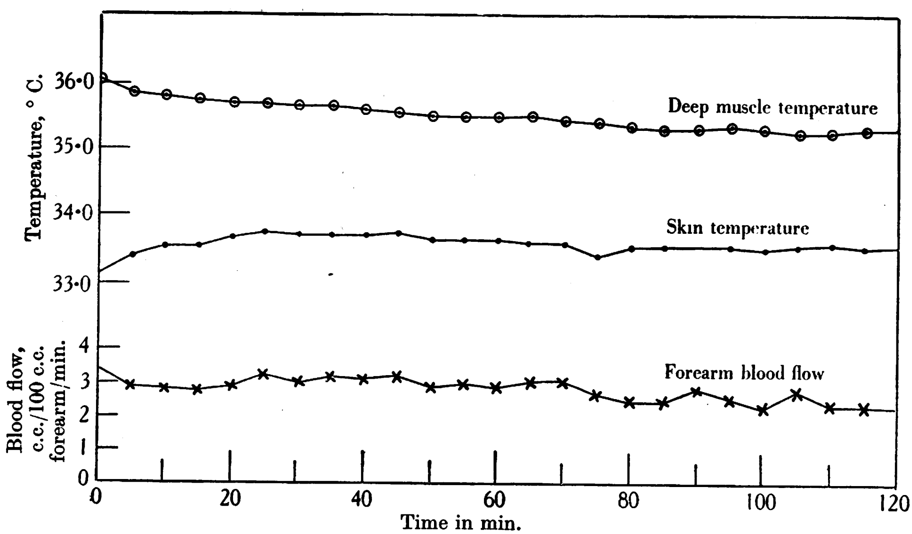

Fig. 4. Blood flow, skin and deep-muscle temperature in the clothed forearm. Average results obtained in seven subjects.

and are shown in Fig. 4. There was a slight rise in skin temperature and a slight fall in deep-muscle temperature over the 2 hr. period of the experiment. The cotton-wool sleeve provided adequate protection from heat loss, since forearm temperatures were maintained at a nearly steady level for 2 hr., and these temperatures were similar to those found in the forearm immediately after baring. During the first 50 min. the blood flow was fairly constant at

$3 \cdot 1 \pm 0 \cdot 25$ c.c./100 c.c. forearm/min. As will be seen from the small standard deviation there was little difference between the seven subjects. During the last 50 min. of the experiment the average figure was only 2·6 c.c. The fall in the rate of blood flow can be accounted for partly by the slight decline in muscle temperature. The figure 3·1 c.c. has been taken as the average blood flow in the clothed arm and is that shown in Table 2.

TABLE 2

	Average blood flow c.c./100 c.c. forearm/min.	Temperature ° C. Skin	Subcutaneous	Deep muscle
Forearm clothed	3·1	33·0	33·6	36·2
Forearm in the water-bath at: 37° C.	5·9	37·0	37·2	36·8
35° C.	4·25	35·0	36·0	36·2
34° C.	3·4	34·0	34·7	35·8
33° C.	2·7	33·0	34·0	35·0
32° C.	2·3	32·0	33·3	34·3
30° C.	1·6	30·0	31·4	32·8

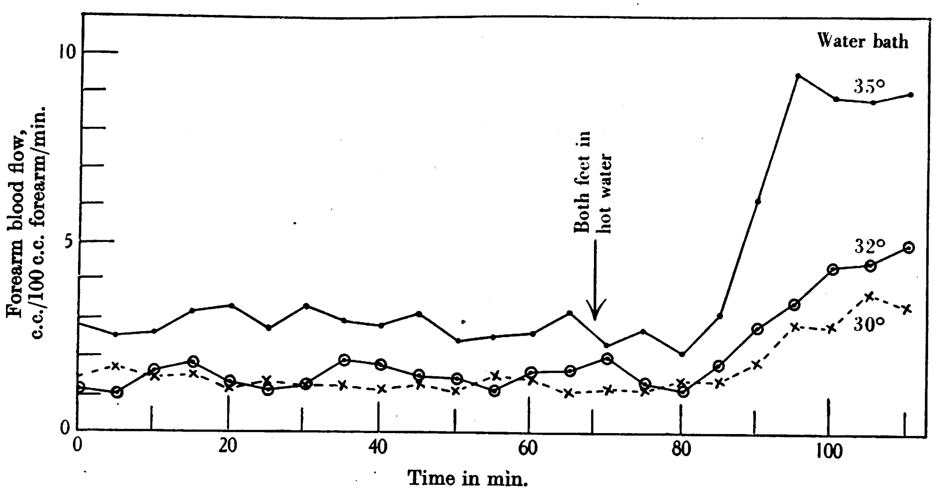

Fig. 5. The effect on forearm blood flow of placing the feet in water at 44–45° C., measured on three separate occasions in the same subject. The forearm was in the water-bath at the water temperature indicated. An increased flow is demonstrated in every case on heating the feet and the effect is considerably emphasized when the forearm bath temperature is raised.

Similar results were obtained when the blood flow and temperature measurements were made on the same arm.

Effect of water-bath temperature on response of forearm blood vessels. In one subject the effect of heat applied to the lower limbs on forearm blood flow was measured. On different occasions the test arm was kept in a water-bath at 30·0, 32·0 and 35·0° C. After a control period of 30 min., the feet and ankles were immersed in water kept between 44·0 and 45·0° C. This produced a rise in body temperature and an increased blood flow in the forearm. The results are shown in Fig. 5. It will be seen that an increased flow was obtained at all three water-bath temperatures, but that the increase was only slight when the arm was in water at 30·0° C., whereas it became progressively greater as the water-bath temperature was raised. The rise in body temperature provoked by the heating of the feet was identical in all three cases.

DISCUSSION

The average temperature of the forearm skin immediately after baring is 33·0° C. This figure is slightly higher than that of 32·4° C. obtained by Benedict (1925). Collier & Maddick (1932) found the skin temperature of the forearm to average 34·0° C. in subjects heavily clothed in sheet rubber. In an environment at 25° C. the average skin temperature of lightly clothed men is 33·0° C. (Burton, 1935). In a group of fifty normal subjects, Eddy & Taylor (1931) found that the skin temperature on the back of the forearm averaged 32·75° C. The subjects were stripped at a room temperature of 20° C., and the skin temperature readings were made 10 min. after stripping. Hardy, Milhorat & Du Bois (1941) state that the skin temperature of the clothed forearm remains constant at 33·8° C. at environmental temperatures of 22–29° C.

Buchthal, Høncke & Lindhard (1944) recorded the temperatures of different muscles. They found that the temperature in the brachioradialis muscle was approximately 35° C., and might be much lower. Their results differ considerably from our own. This may be explained by their use of a shorter needle thermocouple (18 mm. as against 25 mm.). There is a gradient of temperature in the forearm from the deep tissues to the skin, so at a depth of 18 mm. the temperature will be lower than at a depth of 25 mm.

It is not stated by Buchthal *et al.* how long after exposure the muscle temperature was recorded, although it is noted that cooling takes place on exposure.

The figures for skin, subcutaneous tissue, deep-muscle and mouth temperatures, which were obtained immediately after baring the forearm, have been examined for possible correlations. Between all four temperatures there is a degree of possible correlation which is significant between those of skin and subcutaneous tissue, but between those of subcutaneous tissue and deep muscle the significance is not on such a high level. There is only a low level of significance in the correlation between skin and deep-muscle temperatures. Mouth temperature, being largely invariant, does not show a significant correlation with the temperature of the forearm tissues. Hardy *et al.* (1941) found that skin temperature changes were not correlated with rectal temperature.

The average blood flows in the forearm at different water-bath temperatures are shown in Table 2. They were calculated from the results obtained by Barcroft & Edholm (1943) and from other results obtained subsequently. The blood flow in the forearm covered with cotton-wool (3·1 c.c.) is rather less than in the forearm in water at 34·0° C. but definitely greater than the blood flow in the forearm in water at 33·0° C. Table 2 also shows the temperature of the skin, subcutaneous tissue and deep muscle of the forearm immediately after baring and in water at different temperatures. The temperature of the skin was assumed to be the same as the water temperature. The tissue temperatures were taken after a steady state had been reached, the time for this varying with the water-bath temperature (see Fig. 2).

The standard or 'normal' conditions are considered to be those conditions existing in the adequately clothed forearm at rest. The term 'adequately clothed' is used to mean that the covering of the arm is sufficient to maintain a comfortable constant temperature. The conditions in the clothed arm are considered to be closely similar to those found in the forearm immediately after baring. The time interval between baring and obtaining the first temperature readings was sufficiently short to ensure that any cooling that might have occurred would not be significant. This is confirmed by extrapolating the curves obtained for the rate of cooling of the forearm on exposure to room temperature (see Fig. 1). The average error was less than 0·1° C. The state of the forearm covered with cotton-wool is also similar to that of the clothed forearm. The skin and deep-muscle temperatures remained nearly constant over a period of 2 hr. in the covered forearm, and the initial readings were identical with those obtained from the group of normally clothed individuals immediately after baring the arm. It is considered, therefore, that the rate of blood flow in the forearm covered with cotton-wool must be nearly the same as that in the adequately clothed forearm at rest.

These data enable a choice to be made of a water-bath temperature which will ensure the least alteration of forearm conditions from those existing in the clothed forearm. It is not possible to select a water-bath temperature which will not result in some alteration in these conditions. If a water temperature of 35·0° C. is used, the deep-muscle temperature remains constant at the standard level, but both skin and subcutaneous temperatures rise. To keep these last two temperatures constant a bath temperature of 33·0° C. must be used, but this will result in a substantial fall of deep-muscle temperature. Similar conclusions are reached if the rate of blood flow is used as a criterion. At a water-bath temperature of 35·0° C. the blood flow is considerably greater than in the forearm covered with cotton-wool; at 33·0° C. the flow is considerably less. Examination of the conditions existing in the intermediate range shows that there is less net alteration in temperature and that the blood flow is of the same order as that in the covered arm when the forearm is immersed in water at 34·0° C.

What are the advantages of using such a bath temperature apart from the fact that conditions will be as near as can be obtained to those existing in the clothed forearm? Data obtained by using other temperatures may be misleading. Abramson & Fierst (1942) used a temperature of 32·0° C. for their water-bath and found the average blood flow in the forearm to be 1·7 c.c./100 c.c. forearm/min. Pickering (1943) used this figure to calculate the total blood flow to the musculature of the body, assuming the forearm blood flow to represent muscle blood flow. This gave a figure of 500 c.c./min. For the reasons given above, however, the blood flow in a forearm in water at 32·0° C. is not representative of the conditions existing in the clothed body, and the total muscle blood flow as calculated is too low. If the figure of 3·1 c.c., representing the blood flow in the covered arm, had been used for the calculation the total muscle flow would be 900 c.c./min.

Other workers have used lower water-bath temperatures. The use of low temperatures may result in the masking of the response of the forearm blood vessels, owing to their constriction. This is illustrated by the experiment described above in which the degree of increase in forearm blood flow, provoked by placing the feet in hot water, is only slight when the forearm is in water at 30·0° C., is definitely increased when the water-bath is at 32·0° C., and the effect is considerable when the arm water-bath is at 35·0° C. This experiment may explain the original failure of Grant & Pearson (1938) to demonstrate any effect on forearm blood flow when heat was applied elsewhere to the body. They used a water-bath at a temperature of 30·0° C., and before the experiment the subject was kept stripped in a room temperature of 15° C. All forearm temperatures fall when the arm is exposed (see Fig. 1), and the tissues would be kept at a low temperature by such a cold water-bath. The constricted forearm vessels would only react to the strongest stimuli. In fact, Grant & Holling (1938) subsequently reported that they had obtained a definite increase in the forearm blood flow, but this required what may be described as heroic heating.

Temperatures higher than 35·0° C. may also be undesirable, as it has been shown that fluctuations in the rate of blood flow increase with higher water-bath temperatures. In particular, the major fluctuation known as the 'die away' effect is very noticeable at temperatures above 37·0° C. It is concluded that the most satisfactory water-bath temperature to select is one between 33·0 and 35·0° C.

The fact that the arm cools when it is bared is of some practical importance. The use of the plethysmograph for measuring blood flow inevitably means some delay between the initial exposure of the forearm and the final adjustment of the apparatus. When the first blood-flow measurements are made, temperatures in all portions of the forearm may have fallen considerably, so the blood flow will be reduced.

Grant & Pearson (1938) have previously recorded the rate of cooling of the forearm in one subject. In 75 min. the skin and deep-muscle temperatures fell 5·5 and 4·7° C. respectively. In only one of our five subjects was the fall so steep; this may be because our room temperature was slightly higher (18·5° as compared with 15·0° C.). Freeman & Nickerson (1938) recorded the changes in skin temperature at ten different areas of the body, the subjects being nude. After 2 hr. the average forearm skin temperatures had fallen to 30·8° C. at a room temperature of 20·0° C.; when the room temperature was 15·0° C., after 2 hr. the skin temperature averaged 29·0° C. These results suggest that, when the whole body is exposed, the rate of cooling of any given area may be less than if that part is the only one exposed. Indeed, Eddy & Taylor (1931) measured skin temperatures in a group of five normal subjects stripped in a room at a temperature of 20·0° C. and found no significant change after 1 hr. exposure.

Lewis (1927) measured changes in subcutaneous temperature when the arm was placed in water, and found that a steady state was reached within 5 min., irrespective of the bath temperature. It will be seen from Fig. 2 that the subcutaneous temperature may take up to 2 hr. to reach a steady state. These results amplify those previously reported (Barcroft & Edholm, 1943) and emphasize that exposure of the forearm to low and high temperatures produces alteration of the temperature of all tissues. Many authors still conclude, following Lefevre (1911), that such temperature changes are confined to the superficial tissues and do not affect the deeper levels.

SUMMARY

1. The temperatures of the skin, subcutaneous tissue and deep muscle measured in the upper part of the resting forearm immediately after baring were 33·0, 33·6 and 36·2° C. respectively.

2. The average blood flow in the resting covered forearm is 3·1 c.c./100 c.c. forearm/min.

3. These figures are compared with those for the forearm in water at different temperatures.

4. Although it is not possible exactly to reproduce the conditions in the adequately clothed forearm by immersion in water, a water-bath temperature of 34·0° C. produces less alteration in these conditions than any other bath temperature.

5. The use of this water-bath temperature during plethysmographic determinations of the forearm blood flow has some advantages; they are discussed.

6. The various forearm temperatures were measured at short intervals for 2 hr. while the forearm was: (i) Uncovered and exposed to air. The final temperature readings were, skin 27·9° C., subcutaneous layer 28·5° C., deep muscle 30·7° C. (ii) Immersed in water. The final subcutaneous temperatures

ranged from 14·6° C. (water-bath, 12° C.) to 38·7° C. (water-bath, 41° C.). For the deep-muscle layer the corresponding figures were 18·6 and 37·8° C. respectively.

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